DARWIN
dark matter WIMP search with noble liquids

Laura Baudis, for the DARWIN consortium[1]

Physics Institute, University of Zürich, CH-8057 Zürich, Switzerland

E-mail: laura.baudis@physik.uzh.ch

Abstract.
DARWIN (dark matter wimp search with noble liquids) is a design study for a next-generation, multi-ton dark matter detector in Europe. Liquid argon and/or liquid xenon are the target media for the direct detection of dark matter candidates in the form of weakly interacting massive particles (WIMPs). Light and charge signals created by particle interactions in the active detector volume are observed via the time projection chamber technique. DARWIN is to probe the spin-independent, WIMP-nucleon cross section down 10^{-48}cm^2 and to measure WIMP-induced nuclear recoil spectra with high-statistics, should they be discovered by an existing or near-future experiment. After a brief introduction, I will describe the project, selected R&D topics, expected backgrounds and the physics reach.

1. Introduction

Astrophysical observations show that 83% of gravitating matter in our universe is non-luminous and non-baryonic. The dark matter might be in the form of neutral, weakly interacting, stable or long-lived elementary particles, so-called WIMPs, which have eluded direct observation so far. Produced in the early universe, WIMPs would naturally lead to the observed dark matter abundance [1] and are predicted to exist in extensions to the Standard Model of particle physics [2]. Galactic WIMPs may be detected via scatters off atomic nuclei in deep underground experiments [3]. Since expected signal rates are below one interaction per kilogram of target material and year and momentum transfers are around 10 MeV - 100 MeV [4, 5], large detector masses, low energy thresholds and ultra-low backgrounds are essential experimental requirements to directly observe these hypothetical particles. Experiments using xenon [6, 7, 8, 9] and argon [10] as a homogeneous detection medium in a time projection chamber have reached sensitivities of $\sim 10^{-44}$cm^2 for the spin-independent scattering cross section on nucleons. While a factor of five improvement is predicted with data already in hand [8], ton-scale experiments under commissioning [11] or construction [12] will likely probe the cross section region down to $\sim 5 \times 10^{-47}$cm^2. Notwithstanding this remarkable leap in sensitivity, and assuming a local density and velocity distribution which are inferred from astronomical observations, significantly larger detectors are requisite to determine WIMP properties, such as its mass, scattering cross section

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[1] The following institutions are members of the consortium (as of December 2011): ETH Zürich, University of Zürich (CH); Karlsruhe, Mainz, MPIK Heidelberg, Münster (DE); Nikhef (NL); Subatech (FR); Weizmann Institute of Science (IL); INFN (IT): Bologna, L'Aquila, LNGS, Milano, Milano Bicocca, Napoli, Padova, Pavia, Perugia, Torino; Associated groups: Columbia, Princeton, UCLA, Arizona State (USA).

and possibly spin [13]. To convincingly demonstrate the dark matter nature of a signal, a measurement of its interaction rate with multiple target materials is compulsory.

2. Technologies

The DARWIN study [14, 15, 16] is focused on a multi-ton liquid argon and/or xenon experiment rooted in the noble liquid time projection chamber (TPC) technique. The TPCs will record the prompt scintillation light[2] created when a particle interacts in the active detector volume along with the few liberated electrons after they are drifted in a strong electric field[3] and extracted into the vapor phase residing above the liquid. The prompt light signal will be observed by an array of photosensors immersed in the liquid, the electrons will be detected either directly, or indirectly via proportional scintillation in the gas phase with a second array of photosensors. The time difference between the prompt and delayed signals determines the z-position of an event, the spatial distribution of the delayed signal yields its $x - y$-position. The relative size of the charge and light signals, as well as their time structure will be used to distinguish nuclear recoils, as expected from WIMP scatters, from electronic recoils, which make the majority of the background. The spatial resolution allows to define an innermost, low-background volume and to reject fast neutrons, which – in contrast to WIMPs – tend to multiple scatter[4].

DARWIN will immensely benefit from the research and development, and from the construction and operation experience gained with XENON10 [17], XENON100 [18], XENON1T [12], WARP [10], ArDM [11], DarkSide [19], and much of the ongoing work is carried out within the framework of these projects. Here I mention a few studies only, some of these are specific to DARWIN. Other work deals with the cryogenic, gas purification, circulation, storage and recovery systems; with the external water Cerenkov shield and its potential extension with a liquid scintillator (depending on the depth of the underground laboratory – the Gran Sasso Laboratory and the Modane extension are under consideration); with material screening, selection and radon emanation measurements; with high-voltage systems, electrodes and field uniformity simulations; with low-noise, low-power electronics, cables and connectors, trigger schemes, data acquisition and treatment; with Monte Carlo simulations of the expected background noise, of the light collection efficiency and position reconstruction capability; with the design of the time projection chamber, of the cryostat and of the calibration system.

Light and charge response: the light and charge yields of noble liquids when exposed to low-energy nuclear recoils (from neutron or potential dark matter interactions) or electronic recoils (from γ- and β-interactions) are studied by several groups participating in DARWIN. A new measurement of the relative scintillation efficiency $\mathcal{L}_{\text{eff}}$ in liquid xenon [20] shows an $\mathcal{L}_{\text{eff}}$ behavior which is slowly decreasing with energy, with a non-zero value at $3\,\text{keV}$ nuclear recoil energy, the lowest measured point. A similar measurement is ongoing for liquid argon [21]. A measurement of the liquid xenon scintillation efficiency for electronic recoils down to $2.3\,\text{keV}$ is in progress [22]. A preliminary data analysis indicates that the scintillation yield falls with decreasing energy, as predicted by models of scintillation mechanisms in noble liquids [23]. Nonetheless, the scintillation response at $2.3\,\text{keV}$ is observed to be non-zero, confirming that liquid xenon experiments will have a finite sensitivity at such low interaction energies. Measurements of the charge yields of LAr and LXe within the same energy regime are being planned.

Signal readout: the prompt scintillation light is to be observed either with conventional photomultiplier tubes (PMTs) which are low in radioactivity [24] and built to withstand low

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[2] The peak photon emission from the transition of exited dimers into their dissociative ground state is centered around $128\,\text{nm}$ and $178\,\text{nm}$ in liquid argon and xenon, respectively [25].

[3] Typical drift fields are 0.5–$1\,\text{kV/cm}$, with electron velocities around $\sim 2\,\text{mm}/\mu s$ [25].

[4] The mean free path of $\sim$MeV neutrons is in the range of tens of cm.

temperatures and high pressures[5] or with a new, hybrid photodetector (QUPID [26]), which has an extremely low radioactivity content ($<1\,$mBq/sensor for U/Th/K/Co) [24] and works both in liquid argon and xenon. The delayed signal can be observed directly, using detectors with single electron sensitivity and high spatial granularity (large electron multipliers [27]), or CMOS pixel detectors coupled to electron multipliers (GridPix [28]), or via proportional scintillation in the gas phase, using gaseous photomultipliers without dead zones (GPMs [29]), PMTs or QUPIDs.

3. Backgrounds, physics reach and timeline

DARWIN will be an "ultimate" argon and/or xenon dark matter experiment, before the solar and atmospheric neutrinos become the main, possibly irreducible background. It will directly probe WIMP-nucleon cross sections down to $\sim 10^{-48}$cm^2. These cross sections are compatible with recent LHC results, should the dark matter particle turn out to be the neutralino [30, 31, 32]. The external background from gammas, muons and neutrons and the background from detector construction materials will be diminished to negligible levels by external shields, the self-shielding of the noble liquids[6], and the choice of fiducial volumes[7]. More difficult are intrinsic backgrounds from ^{85}Kr and ^{222}Rn decays in xenon and from ^{39}Ar decays in argon. In xenon, the natural krypton concentration is to be reduced by cryogenic distillation to $<1\,$ppt and the radon level in the liquid is to be kept $<1\,\mu$Bq/kg. Argon gas that is extracted from deep underground wells is depleted in the radioactive ^{39}Ar [33]. Still, a background rejection by pulse-shape analysis of $>10^8$ is required in the case of a liquid argon detector [14, 15].
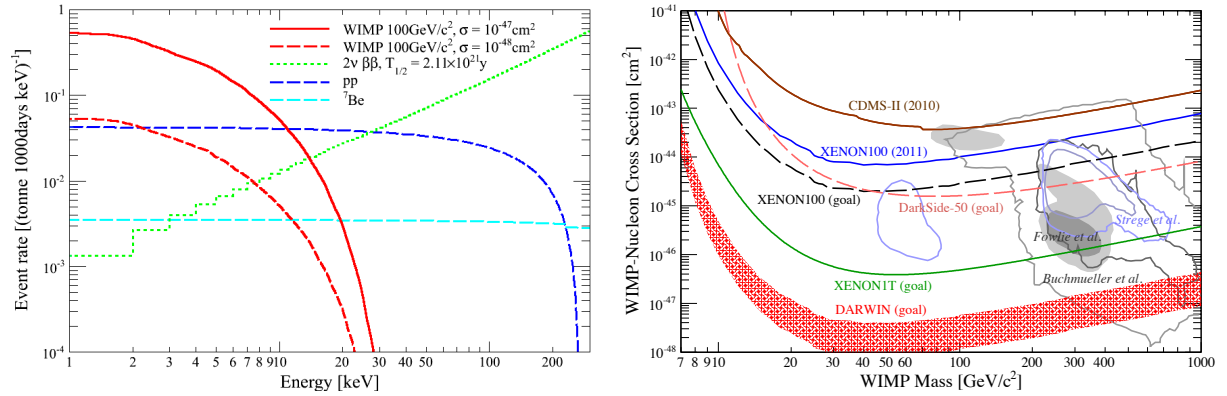

Figure 1. (Left): Expected nuclear recoil spectrum from WIMP scatters in LXe for a spin-independent WIMP-nucleon cross section of 10^{-47} cm^2 (red solid) and 10^{-48} cm^2 (red dashed) and a WIMP mass of $100\,$GeV/c^2 (using the standard halo model as in [13]), along with the differential energy spectrum for pp (blue) and ^{7}Be (cyan) neutrinos, and the electron recoil spectrum from the double beta decay of ^{136}Xe (green), assuming the natural abundance of 8.9% and the recently measured half life of 2.1×10^{21} yr [34]. Other assumptions are: 99.5% discrimination of electronic recoils, 50% acceptance of nuclear recoils, 80% flat analysis cuts acceptance. (Right): DARWIN's sensitivity goal for spin-independent WIMP nucleon cross sections, existing limits from XENON100 [8] and CDMS-II [35], future goals and updated theoretical predictions from supersymmetry (closed contours and shaded regions) [30, 31, 32].

The left side of figure 1 shows the expected nuclear recoil spectrum from WIMP scatters in xenon together with the background from neutrino-electron elastic scatters of solar neutrinos

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[5] One example is the Hamamatsu R11410/R11065 3"-tube for LXe/LAr, currently tested for its performance, long-term stability and radioactivity levels at several DARWIN institutions.

[6] The mean free path of $3\,$MeV gammas is $\sim 9\,$cm and $\sim 20\,$cm in liquid xenon and argon, respectively.

[7] The final choice of the size and target materials are part of the outcome of the study, a baseline scenario is $20\,$t ($10\,$t) total (fiducial) LAr/LXe mass.

and from the double beta decay of ^{136}Xe. The right side shows the aimed sensitivity of DARWIN, along with existing best upper limits on the WIMP-nucleon cross section, projections for the future and theoretically predicted regions from supersymmetric models.

DARWIN, which was endorsed in recent updates to the European and Swiss roadmaps for astroparticle and particle physics [36, 37], has officially started in 2010. A rough time schedule is the following: a technical design study is to be ready in spring 2013, leading to a letter of intent and engineering studies towards the proposal of a concrete facility in spring 2014, and a technical design report for detector construction by the end of 2014. The shield and detector construction phase is to start in 2015, commissioning in late 2016 with the start of the first physics run by mid 2017.

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